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Deflection of high-energy negative particles in a bent crystal through axial channeling and multiple volume reflection stimulated by doughnut scattering

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ABSTRACT

Different kinds of deflection in a silicon crystal bent along the $\langle 111 \rangle$ axis was observed for 150 GeV/c negative particles, mainly π^- mesons, at one of the secondary beams of the CERN SPS. The whole beam was deflected to one side in quasi-bound states of doughnut scattering (DSB) by atomic strings with the efficiency $(95.4 \pm 0.2)\%$ and with the peak position close to the bend crystal angle, $\alpha = 185$ µrad. It was observed volume capture of π^- mesons into the DSB states with a probability higher than 7%. A beam deflection opposite to the crystal bend was observed for some orientations of the crystal axis due to doughnut scattering and subsequent multiple volume reflections of π^- mesons by different bent planes crossing the axis.

When high-energy charged particles enter a crystal with sufficiently small angles to the crystallographic axis their transverse motion is governed by the potential of the lattice of atomic strings averaged along the axis that is the axial channeling regime is realized [1]. The transverse momentum of a particle changes its direction due to scattering by atomic strings. Particles with the orientation angle ψ are distributed along the arc (circle) with the radius ψ around the axis direction as a result of multiple scatterings by atomic strings during the passage through the crystal. This was a reason to call such a process of multiple scattering of particles by atomic strings "doughnut scattering".

The estimate of the crystal length required to obtain a full randomization of the transverse momentums of particles (equalization length) was suggested by Lindhard [1] and for the orientation angle $\psi = \psi_1$ equals

$$\psi_1 = \sqrt{\frac{4Z_1 Z_2 e^2}{pvd}}, \qquad \lambda_1 = \lambda(\psi_1) = \frac{4}{\pi^2 N d a \psi_1}, \tag{1}$$

where ψ_1 is the critical angle for axial channeling, Z_1 and Z_2 are the atomic numbers of the incident particle and the crystal atom, p and v are the momentum and velocity of the particle, d is the interatomic spacing in the string, N is the atomic density in the crystal and a is the screening length for the particle–atom potential ($a = 0.194$ Å for Si). For 150 GeV/c π^- mesons in a silicon crystal oriented along the $\langle 111 \rangle$ axis $\psi_1 = 33.8$ µrad and $\lambda_1 = 26.3$ µm. A full randomization is also possible for $\psi > \psi_1$ but

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it requires larger crystal lengths. Our simulation results show that the real equalization length for our case is about ten times larger than the estimates of λ_n for $\psi = n\psi_1$ given in [2].

The bound states with a single atomic string are also possible for negative particles due to the attractive character of the forces acting between the particles and the atomic strings. The particles in these states move along the precessing elliptical orbits around the strings. The deflection possibility for relativistic negative particles in the bound states with atomic strings in a bent crystal had been shown in the numerical experiment [3] using the model of binary collisions of particles with the crystal atoms.

High energy charged particles in unbound states performing doughnut scattering at the axial orientation of a bent crystal can be also deflected. The condition for the particle deflection in the regime of doughnut scattering had been considered in [2,4]. The deflection occurs if particles have time to finish the momentum randomization around the angular position of the axis changing along the crystal and if the crystal length is not very large. The particles deflecting in this case can be considered as quasi-bound with the axis direction in contrary to the real bound states with a single atomic string. Let us call this regime “Doughnut Scattering Bound” (DSB). The motion regime for particles performing multiple scattering by atomic strings but do not following to the crystal bend will be called “Doughnut Scattering Unbound” (DSUB). Let us note some peculiarities, which are important for understanding the DSUB regime. The particle momentum randomization center is determined by the angular position of the axis therefore it shifts with the penetration of a particle into a bent crystal. Besides, the transverse momentum of a particle, which determines the randomization radius at the given crystal depth, is changed due to Coulomb multiple scattering and doughnut scattering (DSUB) in the previous crystal layers.

The sufficient condition for the particle deflection due to doughnut scattering was formulated in [4] from the requirement that the average square of the particle deflection angle due to multiple scattering by the atomic strings at the exit from a bent crystal should be smaller than the square of the critical angle

$$\overline{\psi^2} = \frac{\lambda L}{R^2} \leqslant \psi_1^2, \tag{2}$$

where R and L are the bend radius and length of the crystal. The deflection of high energy charged particles in the DSB regime, when the condition (2) was fulfilled, was observed for 400 GeV/c protons [5] and 150 GeV/c π^- mesons [6]. In the last case the crystal bend angle as well as the crystal length were small, $\alpha = 43$ μrad $= 1.27\psi_1$ and $L = 0.98$ mm. Therefore, the contribution of the bound states of π^- mesons with single atomic strings was sufficiently large, about 15%, according to the simulation results.

This Letter presents the results of the experiment on the deflection of negative particles, 150 GeV/c π^- mesons, by a bent silicon crystal oriented along the $\langle 111\rangle$ axis with the considerably larger bend angle $\alpha = 185$ μrad $= 5.5\psi_1$. This allowed us to observe the dependence of the particle fraction deflected in the quasi-bound states with the bent axis direction, in the DSB regime, on the crystal orientation. The efficiency of the one side deflection was larger than 95%. It was observed volume capture of π^- mesons into the DSB regime with a probability larger than 7%. Besides, the beam deflection to the side opposite to the crystal bend was observed for some orientations of the crystal axis due to doughnut scattering and subsequent multiple volume reflections of π^- mesons by the bent planes crossing the axis. The last effect of multiple volume reflections in one crystal (MVR OC) predicted in [7] was observed recently for 400 GeV/c protons [8] and 150 GeV/c π^- mesons (will be published).

The experiment has been performed at one of the secondary beams of the CERN SPS. The experimental setup was the same as described in [9]. Four microstrip silicon detectors, two upstream and two downstream of the crystal, were used to measure the particle angles with resolution of $\sigma_a = 8$ μrad, which is limited by the multiple scattering of particles in the detectors and the air. A $70 \times 8 \times 0.3$ mm^3 silicon strip (length × width × thickness) with the largest faces parallel to the (110) planes and with the side faces, which are 70×0.3 mm^2, parallel to the (111) planes fabricated according to the technologies [10,11] was used in our experiment. The crystal was placed with its length along a vertical direction. The beam entered the crystal through its side face nearly parallel to the large ones (see Fig. 1 in [9]). Thus, the $\langle 111\rangle$ axis direction became nearly aligned with the beam. The crystal was mechanically bent along its length. The anticlastic curvature produced along the crystal width was used for the beam deflection in the horizontal plane. Because of a small planar dechanneling length for negative particles the crystal has been preliminary tested using 400 GeV/c proton beam. The crystal bend angle measured through the deflection of protons by the (110) bent planar channels was $\alpha = (185 \pm 0.4)$ μrad.

The condition (2) for the particle deflection due to doughnut scattering is fulfilled for our case, $\overline{\psi^2} = 0.098\psi_1^2$. As it was mentioned above the real equalization length for our case is about ten times larger than the theoretical one used in (2). However, the condition (2) with the real equalization length is still satisfied in our experiment for a narrow beam fraction in the aligned crystal.

The measured divergence of the incident beam of π^- mesons was characterized by the RMS deviations $\sigma_x = \sigma_y = (26.5 \pm 0.2)$ μrad. A high precision goniometer was used to orient the crystal with respect to the beam axis in the horizontal and vertical planes with the accuracy of 2 μrad. At the beginning the scan of the horizontal orientation angles of the crystal θ_h was made to align the (110) planes with the beam by the fixation of the goniometer position corresponding to the deflection efficiency maximum of particles due to planar channeling. Then the alignment of the $\langle 111\rangle$ axis with the beam was performed by the scan of the vertical orientation angles of the crystal θ_v.

Fig. 1(a) shows the beam intensity distribution in the deflection angles of particles in the horizontal θ_x and vertical θ_y planes for the perfect alignment of the crystal with the axis, $\theta_h = \theta_v = 0$, when the fraction of particles deflected with the horizontal angles around α (shown by the dashed line) is maximum. The narrow fraction of the incident beam with the angles $(\theta_{xo}^2 + \theta_{yo}^2)^{1/2} \leqslant 10$ μrad was used. Fig. 1(b) shows the horizontal projection of this distribution by the hatched histogram. The distribution maximum is at the angle $\theta_x < \alpha$. The deflection efficiency to the bent side is $P_d(\theta_x > 0) = (95.4 \pm 0.2)$%. The histogram 2 shows the distribution obtained by simulation for the experimental condition. The model of atomic-string lattice [12] with the atomic potential and electron density obtained in the Doyle–Turner approximation for the atomic scattering factors was used for simulation. The one side deflection efficiency obtained in the simulation $P_d(\theta_x > 0) = (98.5 \pm 0.1)$%. The maximum position of the calculated distribution is about the crystal bend angle. The reduction of the deflection angles in the experimental distribution maximum is explained by the crystal torsion, which leads to different orientations of the crystal axes along the vertical direction. For comparison the histogram 3 shows the deflection angle distribution of π^- mesons calculated for the straight crystal with the same length. The distribution has a Gaussian shape centered at $\theta_x = 0$ with the RMS deviation value $\sigma = (28.65 \pm 0.24)$ μrad, which is larger than the Coulomb multiple scattering angle $\theta_o = 24$ μrad for the amorphous orientation due

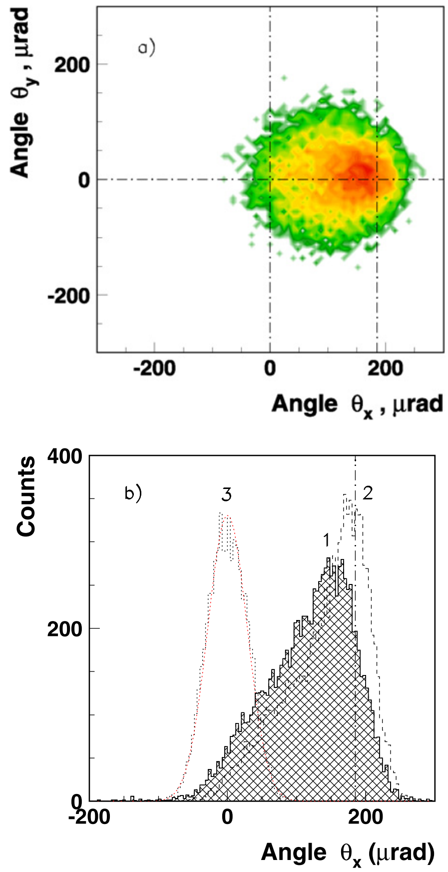

Fig. 1. (Color online.) (a) Beam intensity distribution in the deflection angles of particles in the horizontal θ_x and vertical θ_y planes for the perfect alignment of the crystal with the axis. The narrow fraction of the incident beam with the angles $(\theta_{xo} + \theta_{yo})^{1/2} \leqslant 10$ μrad were selected. The vertical dashed line shows the crystal bend angle value $\alpha = 185$ μrad. (b) The horizontal projection of the experimental distribution (1). The histogram 2 is the simulation result for the same condition. The histogram 3 shows the distribution for the straight crystal obtained by simulation.

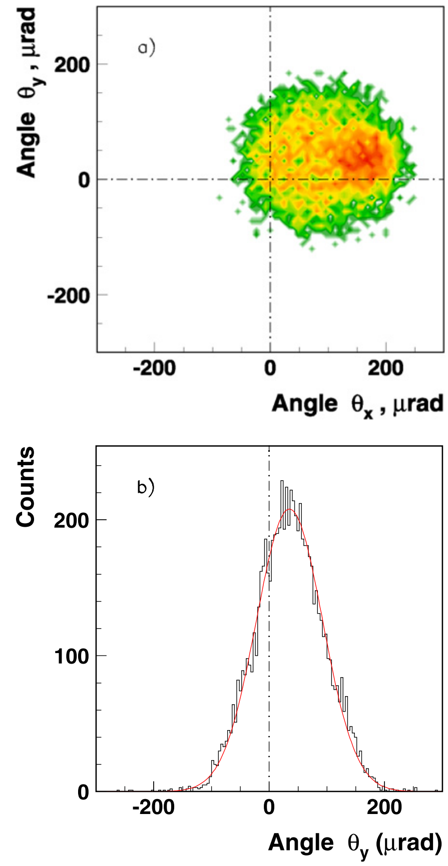

Fig. 2. (Color online.) (a) The same as in Fig. 1(a) for the crystal inclination with $\theta_v = 35$ μrad. (b) The vertical projection of the distribution (a). The mean value of Gaussian fit $m = (35.2 \pm 0.7)$ μrad.

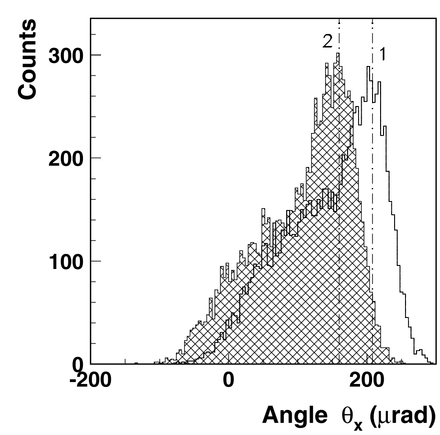

Fig. 3. (Color online.) The distributions of horizontal deflection angles of π^- mesons for the crystal orientation angles $\theta_h = 24$ μrad (1) and -24 μrad (2) obtained by simulation. The dashed lines show the deflection angle values given by the crystal $\theta_{xd} = \alpha + \theta_h$.

to the contribution of doughnut scattering by the atomic strings of the crystal.

The interesting peculiarity of the beam deflection by a bent crystal in the case of its axial orientation exists. When there is a small vertical inclination of the incident beam relative to the crystal bend plane, $\theta_{yo} \leqslant \psi_1$, where the bent atomic strings are located, the beam particles obtain also some vertical deflection returning them back to the bend plane. For particles in the quasi-bound regime of doughnut scattering the distribution maximum position of the vertical deflection angles is at $\theta_y = -\theta_{yo}$ as in the case presented in Fig. 2. For particles in the unbound regime of doughnut scattering the vertical deflection occurs also but its value is smaller than θ_{yo} as it was found by our simulation.

Let us consider how possibility for the π^- meson beam deflection in the quasi-bound regime DSB changes with changing the orientation of the crystal axis with the beam in the bend plane. Fig. 3 shows the distributions of horizontal deflection angles of π^- mesons for the crystal orientation angles $\theta_h = 24$ μrad (1) and -24 μrad (2) obtained by simulation. The distributions have well seen maximum on the right generated by particles deflected in the quasi-bound regime DSB. The distribution maximum positions are determined by the deflection angle given by the bent crystal in the case of its inclination with the beam, $\theta_{xd} = \alpha + \theta_h$ (these values are shown by the dashed lines). The distribution tail to the side of the initial beam direction increases in comparison with the perfect alignment of the crystal and it acquires a convex shape. Let us note that the crystal-beam mutual orientation is always changed by the crystal inclination in the experiment. However, it is sometimes more convenient to talk about the beam incident angles, which are $\theta_{xo} = -\theta_h$ and $\theta_{yo} = -\theta_v$.

Fig. 4 shows the dependence on the beam incident angle θ_{xo} for the beam fraction of π^- mesons deflected by the angles around θ_{xd} with $|\theta_x - \theta_{xd}| < 32$ μrad obtained in the experiment (1) and by simulation (2). The dependence difference is explained by the torsion of the crystal used in the experiment. It should be noted that there are also particles in the unbound regime DSUB in the considered interval of the horizontal deflection angles. However, the dependences demonstrate mainly the reduction with the value of θ_{xo} the quasi-bound fraction value (3) obtained by simulation. All particles in the DSB regime with the incident angles $|\theta_{xo}| > \psi_1$ were captured in the crystal volume due to Coulomb multiple scattering by the crystal nuclei and due to doughnut scattering by atomic strings. Possibility for volume capture of π^- mesons into the DSB regime remains along the whole arc of the bent crystal as it is seen for the positive values of θ_{xo} in Fig. 4. The corresponding volume capture probability is larger than 7%.

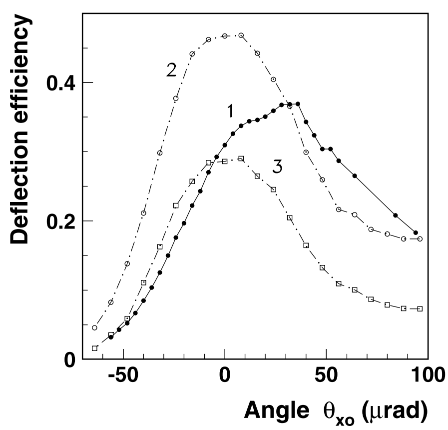

Fig. 4. (Color online.) The dependence on the beam incident angle θ_{xo} for the beam fraction of π^- mesons deflected by the angles around θ_{xd} with $|\theta_x - \theta_{xd}| < 32$ μrad obtained in the experiment (1) and by simulation (2). Curve 3 shows the quasi-bound deflected fraction of π^- mesons with $((\theta_x - \theta_{xd})^2 + \theta_y^2)^{1/2} < \psi_1$ obtained by simulation.

Fig. 5 shows the deflection angle distributions of π^- mesons for different crystal orientations, which are far from the perfect alignment. For $\theta_h = 50$ μrad (a) the distribution is formed due to unbound states of doughnut scattering of π^- mesons in the condition when the crystal axis direction becomes farther from the incident beam direction with increasing the penetration depth of particles into the crystal. The distribution maximum is close to $\theta_x = 0$. The partial randomization of the transverse momentum of particles leads to the arc shape distribution with the average radius larger than θ_h but smaller than $\alpha/2$. The distribution tail stretches significantly farther than the bend angle α because there are particles acquired considerable vertical momentum components due to doughnut scattering in the previous layers of the crystal. For the crystal orientation angle $\theta_h \approx -\psi_1$ (b) the particle fraction in the DSB regime is well seen through the maximum on the right. In this case, the volume capture of particles into the DSB regime occurs as it was discussed above.

For the crystal orientation angle $\theta_h \approx -\alpha/2$ (c) the tangency area of the incident beam with the bent axes is about the middle of the crystal where the initial negative angular position of the axes changes to the positive one. Let us remember again that the axis position is the center of the particle momentum randomization in the DSUB regime. The deflection angle distribution is very wide and approximately centered at $\theta_x = 0$ in this case. The hatched histogram shows the distribution obtained for the amorphous crystal orientation far from the axes and plane directions

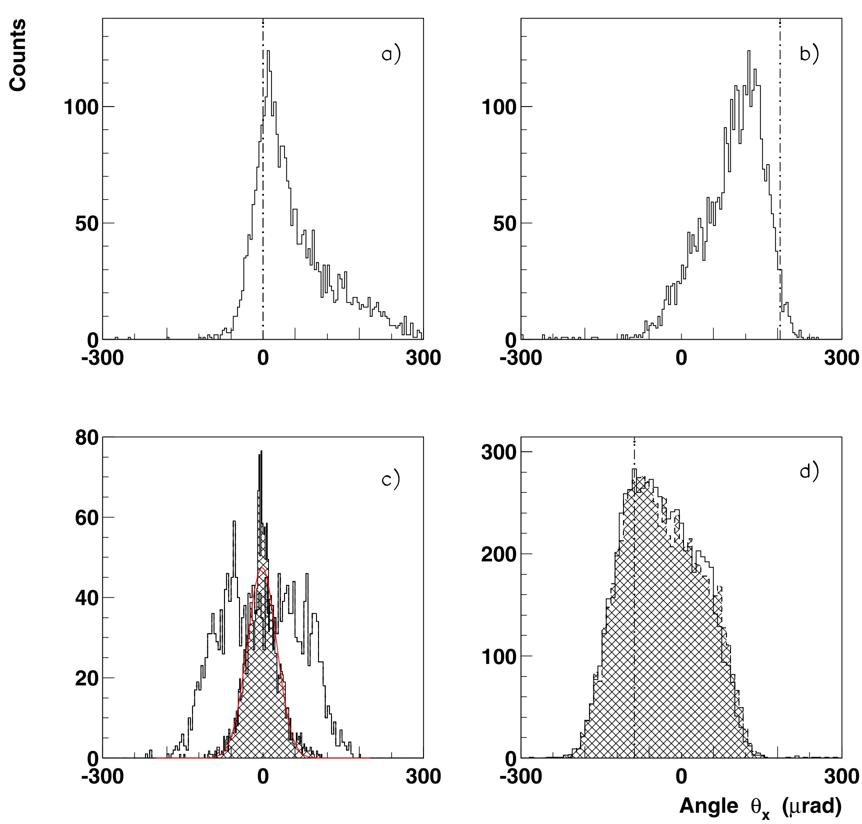

Fig. 5. (Color online.) The horizontal deflection angle distributions of π^- mesons for different crystal orientations far from the perfect alignment. (a) $\theta_h = 50$ μrad, (b) $\theta_h = -32$ μrad, (c) $\theta_h = -89$ μrad, (d) $\theta_h = -129$ μrad. The dashed line in (b) shows the value of the deflection $\theta_{xd} = \alpha + \theta_h$ and in (c) it shows the maximum position $\theta_x = -88$ μrad. The hatched histogram shows the distribution for the amorphous orientation of the crystal in (c) and the distribution obtained by simulation for the same condition in (d).

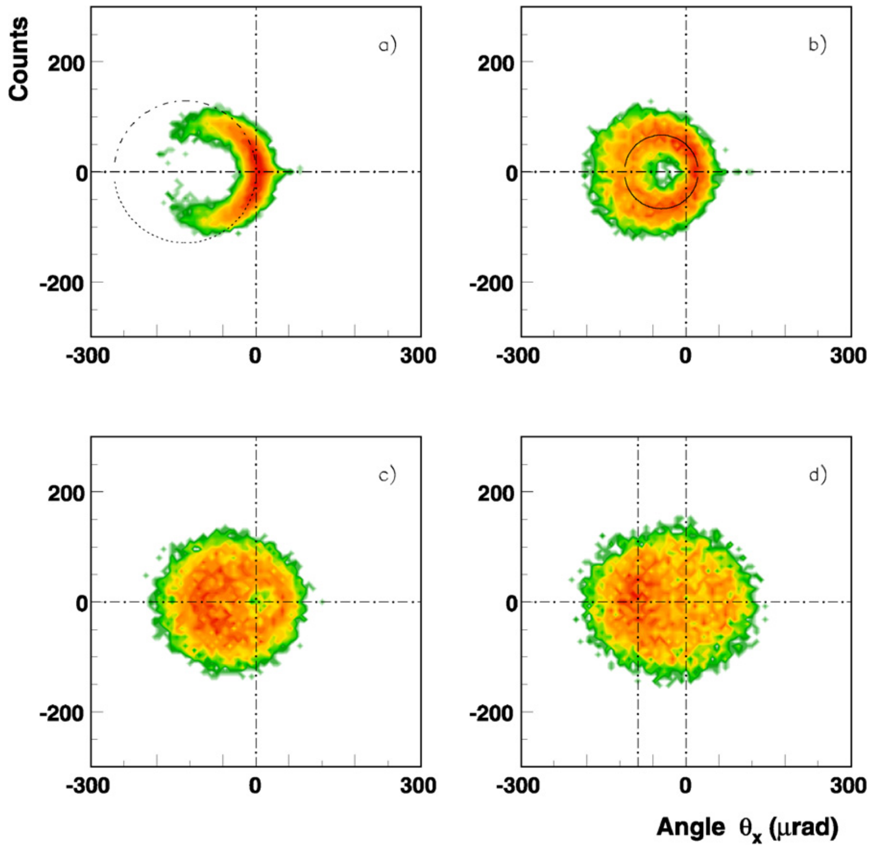

Fig. 6. (Color online.) The beam intensity distributions in the deflection angles obtained by simulation for the case presented in Fig. 5(d), the crystal orientation $\theta_h = -129$ μrad, at the different penetration depths of the beam into the crystal: 2 mm (a), 4 mm (b), 6 mm (c) and 8 mm (d). The circle shown by dashed line in (a) has the center at $\theta_x = -\theta_h$ and the radius $R = \theta_h$. The transverse momentum randomization of π^- mesons occurs along this circle in the straight crystal. The distribution maximum position is shown by the dashed line in (d).

(the distributions are not equally normalized). Doughnut scattering of particles by bent atomic strings for the crystal orientation with $\theta_h \approx -\alpha/2$ increases the beam broadening about three times in comparison with the amorphous orientation.

The effect of the beam deflection unexpected for the axial crystal orientation was observed for the angles $\theta_h < -\alpha/2$. The tangency areas of the initial momentum directions of particles are closer to the crystal exit in this case. For the case presented in Fig. 5(d) $\theta_h = -129$ μrad. The distribution maximum is on the side opposite to the bend at $\theta_x = -88$ μrad. This deflection is larger than it was observed in our experiment for 150 GeV/c π^- mesons in the conditions of multiple volume reflections in one crystal (MVR OC) by bent planes crossing the $\langle 111 \rangle$ axis (will be published), which was about $\theta_{mvr} = 50$ μrad. The effect MVR OC occurs when the ratio between the bend angle and the incident beam angles is α:θ_{xo}:$\theta_{yo} = 4$:2:1. Besides, particles should have large vertical angles with the axis, $\theta_{yo} \gg \psi_1$, to be reflected by planes. The hatched histogram shows the distribution obtained by simulation for the experimental conditions. The agreement is very well because the crystal torsion should not be very important for the regime of unbound doughnut scattering of particles realizing in this case.

Fig. 6 shows the beam intensity distributions in the deflection angles obtained by simulation for the case presented in Fig. 5(d) at the different penetration depths of the beam into the crystal. The axis direction at the crystal entrance coincides with the center of the circle with the radius $R = \theta_{xo}$ shown in Fig. 6(a) for the depth $Z = 2$ mm. Particles at this depth are partly randomized along the arc with some radius, which is smaller than θ_{xo} because of the crystal bend. Many particles obtain large vertical momentums due to this randomization. They obtain also negative horizontal deflections. Therefore, the tangency areas of their momentums with bent planes crossing the axis become closer to the crystal entrance than for the initial beam direction. These changes of transverse momentums of particles relative to the bent axis inside the crystal due to doughnut scattering lead to the realization of the MVR OC for a large part of the beam. This forms the distribution maximum at $\theta_x < \theta_{mvr}$ (see Fig. 6(b)–(d)) because the MVR deflection is added to the negative deflections already obtained due to doughnut scattering of these particles in the previous crystal layers.

Fig. 7 shows for comparison the deflection angle distribution of π^- mesons for the straight crystal of the same length with the same orientation angle, $\theta_h = -129$ μrad, obtained by simulation. This is the arc distribution around the fixed center determined by the crystal axis direction, which coincides with the center of the circle of the radius $R = |\theta_h|$ shown by the dashed line in Fig. 7(a). The horizontal projection of the distribution is shown in Fig. 7(b). It has only a very small negative shift of its maximum and can be compared with the corresponding distribution for the bent crystal (Fig. 5(d)).

Our experiment has shown possibility to deflect high energy negative particles in the quasi-bound regime of doughnut scattering DSB by the angles significantly larger than the critical angle ψ_1. The dependence of the beam fraction deflected in the DSB regime on the crystal orientation was obtained. The large bend angle allowed to observe the volume capture of π^- mesons into the DSB regime, whose probability was larger than 7%. Particles in the DSB regime move along the bent atomic strings. Therefore, at the

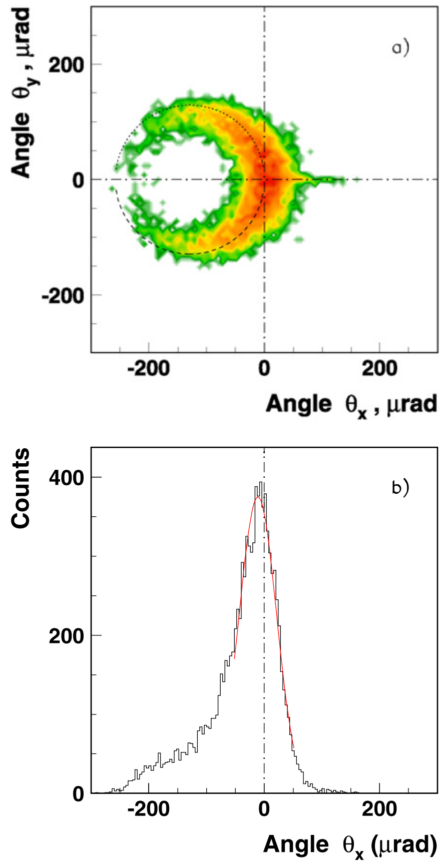

Fig. 7. (Color online.) (a) The deflection angle distribution of π^- mesons for the straight crystal of the same length with the same orientation angle, $\theta_h = -129$ μrad, obtained by simulation. The randomization circle is shown like in Fig. 6(a). (b) The horizontal projection of the distribution shown in (a).

vertical inclination of the bend plane θ_v they obtain also the corresponding vertical deflection $\theta_y = \theta_v$. The beam deflection opposite to the crystal bend for large orientation angles was observed, which was stimulated by doughnut scattering of π^- mesons in the previous crystal layers. Efficient axial deflection by short bent crystals can be useful for the beam collimation of high energy negative particles.

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References

[1] J. Lindhard, K. Dan, Vidensk. Selsk. Mat. Fys. Medd. 34 (14) (1965).
[2] J.F. Bak, et al., Nucl. Phys. B 242 (1984) 1.
[3] A.M. Taratin, S.A. Vorobiev, Phys. Lett. A 72 (1979) 145.
[4] N.F. Shul'ga, A.A. Greenenko, Phys. Lett. B 353 (1995) 373.
[5] W. Scandale, et al., Phys. Rev. Lett. 101 (2008) 164801.
[6] W. Scandale, et al., Phys. Lett. B 680 (2009) 301.
[7] V. Tikhomirov, Phys. Lett. B 655 (2007) 217.
[8] W. Scandale, et al., Phys. Lett. B 682 (2009) 274.
[9] W. Scandale, et al., Phys. Rev. Lett. 101 (2008) 234801.
[10] S. Baricordi, et al., Appl. Phys. Lett. 91 (2007) 061908.
[11] S. Baricordi, et al., J. Phys. D: Appl. Phys. 41 (2008) 245501.
[12] A.M. Taratin, S.A. Vorobiev, Phys. Lett. A 115 (1986) 401.